MICHIGAN STATE UNIVERSITY
CYCLOTRON LABORATORY

ECR ION SOURCE DEVELOPMENT FOR SUPER-STRIPPED POSITIVE IONS IN ACCELERATOR AND ATOMIC PHYSICS APPLICATIONS

T. A. ANTAYA

INVITED TALK AT THE TENTH CONFERENCE ON THE
APPLICATION OF ACCELERATORS IN RESEARCH AND INDUSTRY
NOVEMBER 7-9, 1988, DENTON, TEXAS

JANUARY 1989

MSUCP-54

MSUCP #54

January, 1989

ECR ION SOURCE DEVELOPMENT FOR SUPER-STRIPPED POSITIVE IONS IN ACCELERATOR AND ATOMIC PHYSICS APPLICATIONS

T.A. ANTAYA
National Superconducting Cyclotron Laboratory*
Michigan State University
E. Lansing, MI 48824, USA

The present generation of Electron Cyclotron Resonance Ion Sources (ECRIS), operating in the frequency range of 6-18 GHz, can produce fully stripped ions up to Z=20 and extending to 30-35+ ions for Z=50-90 [1]. To obtain even higher charges, the next generation of ECR sources may employ superconducting magnets for resonance heating at 28 GHz. This frequency matches gyrotron microwave sources developed for ECR heating in plasma fusion experiments. Higher frequency operation permits, in principle, operation at higher plasma densities, by raising the cutoff limit, and there is now evidence that both the peak and average charges extracted from ECR sources scale with the plasma density [2]. In order to further study these issues, a superconducting magnet structure for a variable frequency ECR, the SC-ECR at NSCL, is now under construction [3-5]. In this paper, the background for this line of source development will be reviewed, and the design and present status of the SC-ECR will be presented.

1. INTRODUCTION

The advancement of positive ion sources of all types has occurred primarily through empirical studies of the effects of changes in source parameters, and ECRIS are no exception. Attempts to model source phenomena have been made-- but the model assumptions are almost always incorrect. Nevertheless, to establish a context for the line of ECRIS development to be discussed in this paper, it is necessary to first review some aspects of the (poorly understood) ion formation model in ECRIS.

While recent ionization measurements show that the step size can be more than one electron removed, especially for low and intermediate charge ions [6], the production of multiply-charged ions in ECRIS generally proceeds sequentially from a few electrons removed to many electrons removed. The mechanism is inelastic collisions of resonantly heated electrons with neutral atoms and ions in the plasma. The sequential character of the ionization process in ECRIS can easily be seen by pulsing the microwave power feed. Low charge ions begin to form a few microseconds after the onset of the pulse, while the highly charged ions take tens of milliseconds to reach equilibrium. To produce super-stripped heavy ions like U^{50+} in ECRIS, it would help to raise the average ion lifetime, τ, relative to all losses. However the ion lifetime is not a directly accessible tuning parameter.

With successive electron impact ionization, the rate of removal of the jth bound electron, R_j, depends on the electron density n_e, the electron velocity v_e, and the cross-section σ_j for the relevant ionization channel,

$$R_j \propto n_e v_e \sigma_j \qquad (1)$$

Raising the electron velocity to raise the ionization rate is not as effective as boosting the plasma density, since ionization cross-sections decline with very high electron velocities. Even if this were not so, the acceleration of electrons to the required keV energies for ionization is quite straight-forward in an ECRIS, and we are generally not concerned with obtaining sufficienly energetic electrons. Loosely speaking, our requirements for the production of super-stripped ions reduce as a result to consideration of the other important terms, n_e and τ. In particular, there is direct evidence for density scaling of the ionization rates in ECRIS, as will be discussed.

At present, ECRIS that produce very highly charged ions are two stage devices [7-12]. In two stage ECRIS, a low charge plasma produced in the first stage diffuses across a pressure gradient to a second stage where further ionization occurs at substantially reduced neutral pressure. Since all of these sources have similar performance, the detailed nature of the first stage, which varies greatly, is probably not as important as having one. This does not preclude the possibility of equivalent performance in a single stage source. For example, improved magnetic confinement at low pressure in a single stage ECR should have the same effect.

Two stage ECRIS developments have not lead to unlimited gains in intensity with charge. The optimum radial multipole order has been studied, with some subtle but no strong multipole order effects observed [13-15]. In ECRIS having a tunable radial fields, wall mirror strengths of the order of the axial mirror strengths are found to be optimal [16-18]. The surprizing results in the small Caprice ECR source suggests that more work needs to be done in the areas of microwave coupling and magnetic confinement [19].

2. ECRIS FREQUENCY SCALING

Since resonant microwave heating of electrons is the plasma drive in these devices, microwave injection into the plasma is of course essential under all operating conditions. Elementary theory predicts that the injected wave will attenuate at the plasma edge when the frequency (ω_{ecr}) of this wave becomes less than the plasma frequency (ω_p):

$$\omega_{ecr} < \omega_p \qquad (3)$$

where, assuming a non-dielectric, non-magnetic and collisionless plasma,

$$\omega_p^2 = 4\pi e^2 n_e / m_e \qquad (4)$$

The limit on the plasma density for microwave heated plasma is then

$$\omega_{ecr} = \omega_p \qquad (5)$$

and we obtain by substitution

$$n_{e,max} = (m_e / 4\pi e^2)\omega_{ecr}^2 \qquad (6)$$

that the maximum allowed plasma density is limited by the heating frequency. If Eq. 6 holds true in ECRIS, there is here a very rare instance of a theoretical prediction of the existence of limiting phenomena, as anyone who has worked on positive ion sources would appreciate.

By 1984, two stage ECRIS had been built over the frequency range of 5-10 GHz, which would give a factor of 4 difference in the maximum allowed plasma density. However, the maximum charges and intensities obtained in the existing sources over this range of frequencies were not significantly different, suggesting that this cutoff condition is not an important design criteria. There were several possible explanations for this lack of a frequency dependence on the performance. First, the simplifying assumptions in the elementary derivation may not be appropriate for an ECR ion source. Second, if the theory did apply, perhaps a factor of four difference in the maximum density was not a large enough change to make a qualitative difference in performance. Third, if the theory did apply, and a factor of four difference was qualitatively significant, these sources may not have been operating at the plasma density limit.

Since then, the existence of a frequency dependence on the maximum density, and value to the ionization rate of raising the frequency, have been confirmed in a set of studies at 10, 16.6 and 18 GHz in Grenoble that were able to operate near cutoff [20-22]. Fig. 1 shows a comparison of source operation at 10 and 16.6 GHz for the production of argon ions from these studies. As can be seen, there is a substantial increase in the intensities of the highest observed charges. Many species in addition to argon were studied, and to summarize those results, it was found that the total extracted current increased by the ratio of the square of the ECR frequency, and the average charge state increased with frequency [23]. The scaling of the total extracted current with frequency indirectly confirms the plasma density scaling with frequency, since the total extracted current is proportional to the confined plasma density. The increase in the average charge, due to large increases in intensity of the highest charges, indirectly confirms that the ionization rate increased with increasing density.

These experiments were not without some difficulties. The same fixed strength permanent magnet hexapole was used for operation at all three frequencies, and this may have been optimum. Second, the source operation was pulsed, to minimize the stress on the high frequency klystron amplifiers, while many ECRIS applications require CW beams. There is no guarantee that similar scaling results will hold for CW high frequency operation, but in long pulse operation (0.5 sec/sec) of the Grenoble source at 18 GHz, 70 eμA of S^{12+}has been obtained, and recently it was reported that 1.0 eμA levels of Ta^{29+} and U^{33+} have been obtained at 16.6 GHz in the first CW operation tests [24]. The step from 10 to 16.6-18 GHz, where the Grenoble work was performed, represents a factor of 3.2 increase in the cutoff plsama density, and resulted in large increases of intensity with charge. Clearly, further work in this area is warranted. A further increase in frequency to 30 GHz would result in an equivalent increase in the cutoff density over operation at 18 GHz, and this would be the next likely qualitative step to take for further studies of ion production scaling in ECRIS.

3. THE SC-ECR DESIGN

NSCL has undertaken to build an ECRIS with a resonance frequency range of 5-35 GHz, for further study of frequency scaling in ECRIS. The corresponding resonance field range is 0.18-1.25 Tesla. A full superconducting coil set is used to produce the required radial and axial filed profiles. It will then be possible in a single geometry to study scaling at and beyond existing levels with a magnetic field that can be optimized at each frequency. The upper limit for first harmonic operation is set to reach existing gyrotron tubes at 28-35 GHz. The SC-ECR will become the primary ion source for the K800 cyclotron at NSCL [25].

In order to minimize the development time of the SC-ECR, the general design parameters of the existing NSCL 6.4 GHz RT-ECR has been adopted. The SC-ECR has two minimum B magnet stages. The main stage length and bore are 50 cm and 14 cm respectively. The overall source configuration is shown in Fig. 2. The magnetic axis is vertical, with an integral iron return yoke as the outside wall of the cryostat and the main structural support. The vacuum pumping scheme is the same as the RT-ECR, where careful optimization has resulted in a gas consumption rate of less than .02 SCCM for most species. The large bore will allow an independently tunable first stage (as shown), or alternatively, a single feed with internal coupling (not shown), which may be more appropriate at with gyrotrons.

To study the transition from operation at existing heating frequencies of 5-18 GHz, to that at 28-35 GHz, the magnetic field must be adjustible over a wide range. Figs. 3-4 show the design axial and radial field profiles. The iron yoke is far from saturation at the highest coil excitations, so the field profile scales linearly with coil excitation over the whole operating range.

4. PRESENT STATUS

At the present time the main elements of the magnet design are complete, and we are now testing winding concepts for the hexapole and solenoid coils. Prototype hexapole coils have been operated to the critical current quench limit without training, and we are now working on the solenoid coils. Correct single coil testing, followed by test operation of the full 6 coil hexapole, without and then with the solenoid coils, will be performed in a large test dewar at NSCL before final assembly of the magnet. The components necessary to complete the magnet as an ion source are being fabricated in parallel with the magnet testing, so that source operation should follow shortly after full operation of the magnet. We now anticipate that these activities will be completed near the end of 1988, with first operation of the ion source in January 1989.

Initial operation will occur at 6.4 GHz, using existing klystron amplifiers at NSCL. At 6.4 GHz the operation and performance should be equivalent to the RT-ECR, and this will be a good reference for future development of the SC-ECR. It will also be possible to study alternate magnetic geometries at 6.4 GHz, by changing the magnetic confinement and microwave coupling over a broad range with the SC-ECR magnet. The next step in frequency is likely to be to 14 GHz, also using a klystron amplifier.

Beyond 14 GHz, a specific rf source has not been selected, because we want to go directly to a gyrotron oscillator at 28-35 GHz, and there are not at present any such systems that would be a good match to an ECRIS. Gyrotrons have been developed primarily for plasma fusion experiments, where high peak power (>100kW) and low duty factor (msec/sec) have been required [26]. At the present time we are working with Varian to develop a intermediate power (10-20kW), CW gyrotron rf source concept at 28 GHz that would be a good match to the SC-ECR.

REFERENCES

[1] J. Parker, ed.,Proc. Int. Conf. ECR Sources, MSUCP-47 (1987).

[2] R. Geller, et.al.,Nucl. Instr. Meth. A243(1987)244.

[3] T. Antaya, et.al., Proc. Int. Conf. ECR Sources, MSUCP-47 (1987)312.

[4] T. Antaya, et.al., Proc. 1988 Appl. Supercon. Conf., IEEE Trans. Mag. (1989) to be published.

[5] T. Antaya, Int. Workshop ECR Sources, Grenoble (1988) to be published.

[6] A.M. Hawold, et.al., Phy. Rev. Letters 56 (1986) 1675

[7] C.M. Lyneis, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)1.

[8] F.W. Meyer, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)10.

[9] R. Geller and B. Jacquot, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)31.

[10] H. Beuscher, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)58.

[11] T. Antaya and Z.Q. Xie, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)72.

[12] A. Chevalier and Y. Jongen, 7th Int. Workshop on ECR Sources, Julich, FRG (1986)266.

[13] C.M. Lyneis and T.A. Antaya, 6th Int. Workshop on ECR Ion Sources, Berkeley, CA (1985)63.

[14] F. Boug, et. al., 6th Int. Workshop on ECR Ion Sources, Berkeley, CA (1985)174.

[15] E. Conard, et. al., Proc. Int. Conf. ECR Sources, MSUCP-47 (1987)67.

[16] R. Geller, private comm.

[17] H. Beuscher, private comm.

[18] Y. Jongen, private comm.

[19] B. Jacquot and R. Geller, Proc. Int. Conf. ECR Sources, MSUCP-47 (1987)251.

[20] R. Geller, et. al., 6th Int. Workshop on ECR Ion Sources, Berkeley, CA (1985)1.

[21] R. Geller, ibid [2].

[22] R. Geller, et. al., 7th Int. Workshop on ECR Sources, Julich, FRG (1986)187.

[23] P. Sortais, These Docteur, Universite Scientifique et Medicale de Grenoble (1985) unpublished.

[24] G. Melin, et.al., Int. Workshop ECR Sources, Grenoble (1988) to be published.

[25] R. Blosser, et.al., Proc. 11th Int. Conf. Cyclotrons, ICONICS, Tokyo (1987)157.

[26] J. Craig, et.al., Proc. Int. Conf. ECR Sources, MSUCP-47 (1987)131.

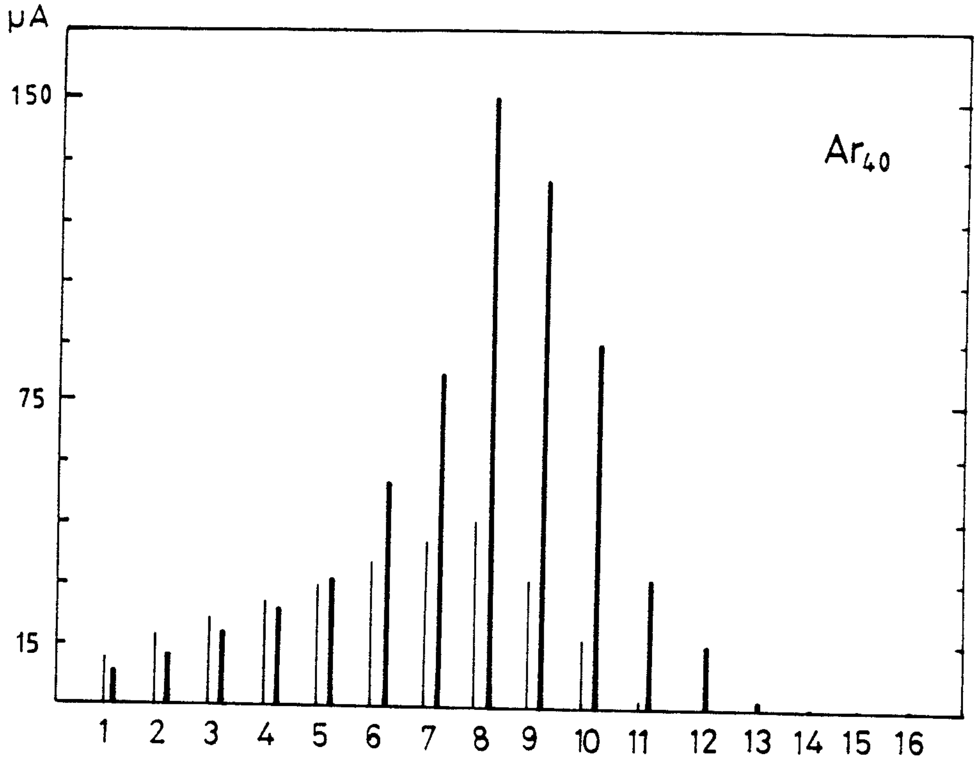

Figure 1. Extracted currents of multiply-charged argon ions are shown for 10 GHz (light lines) and 16.6 GHz (dark lines) operation of the frequency scaling ECRIS at Centre D'etudes Nucleaires Grenoble [23].

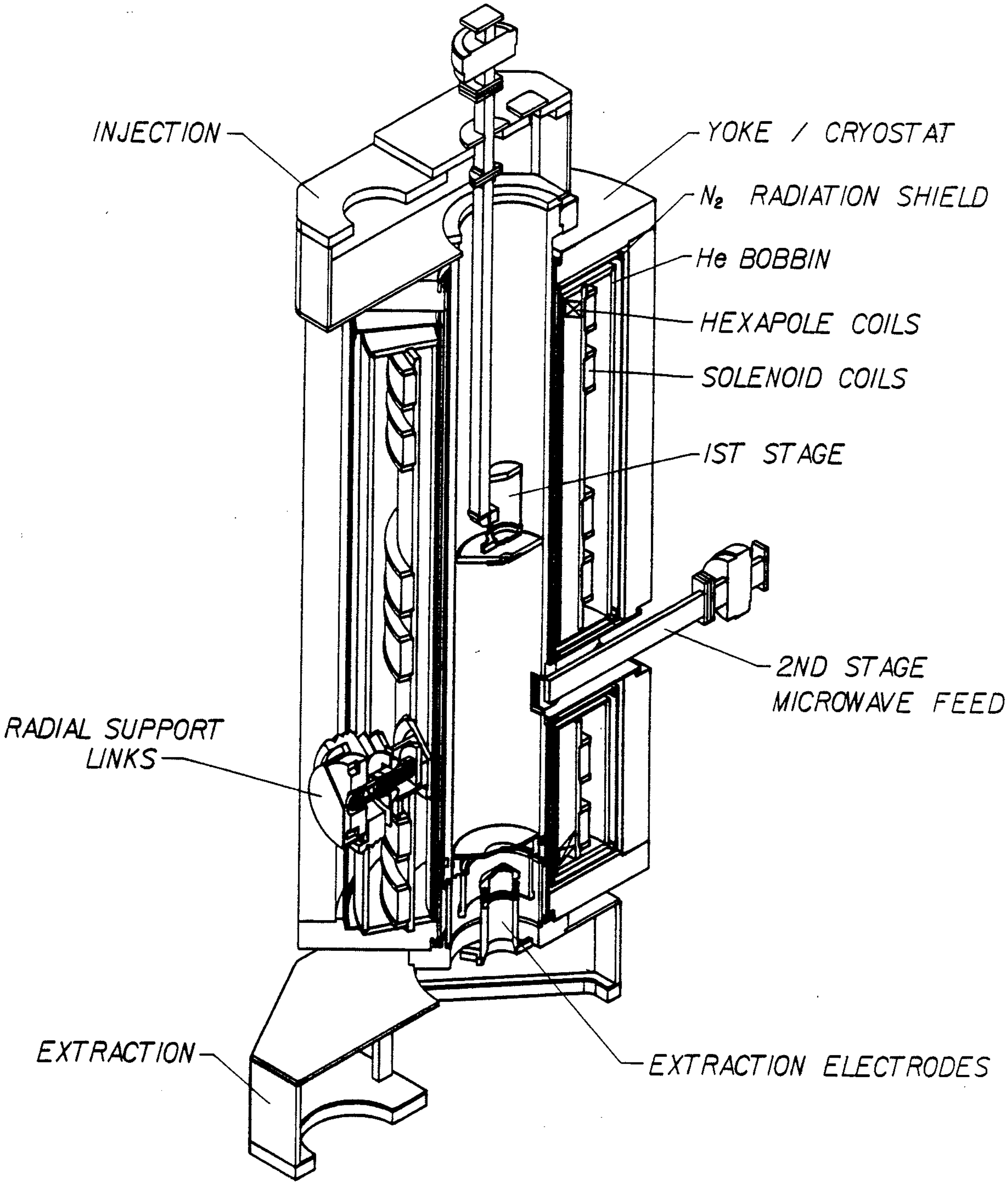

Figure 2. The present design configuration for the SC-ECR ECRIS now under construction at NSCL.

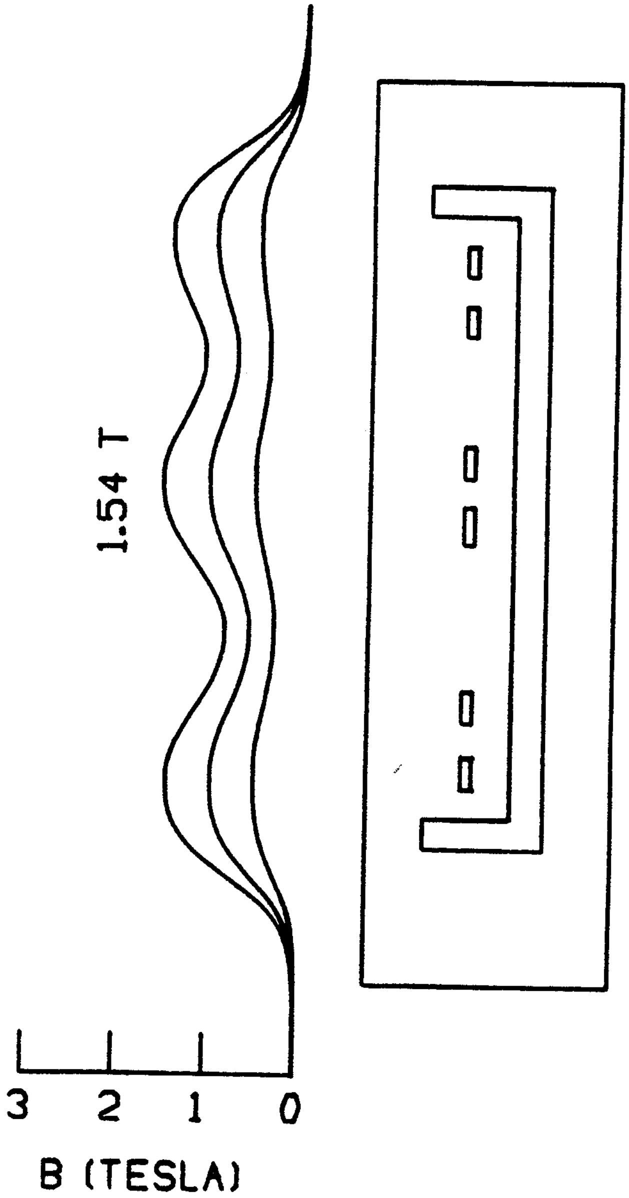

Figure 3. The design axial magnetic field profile of the SC-ECR is shown for 1/3, 2/3, and full excitation of the solenoid coils.

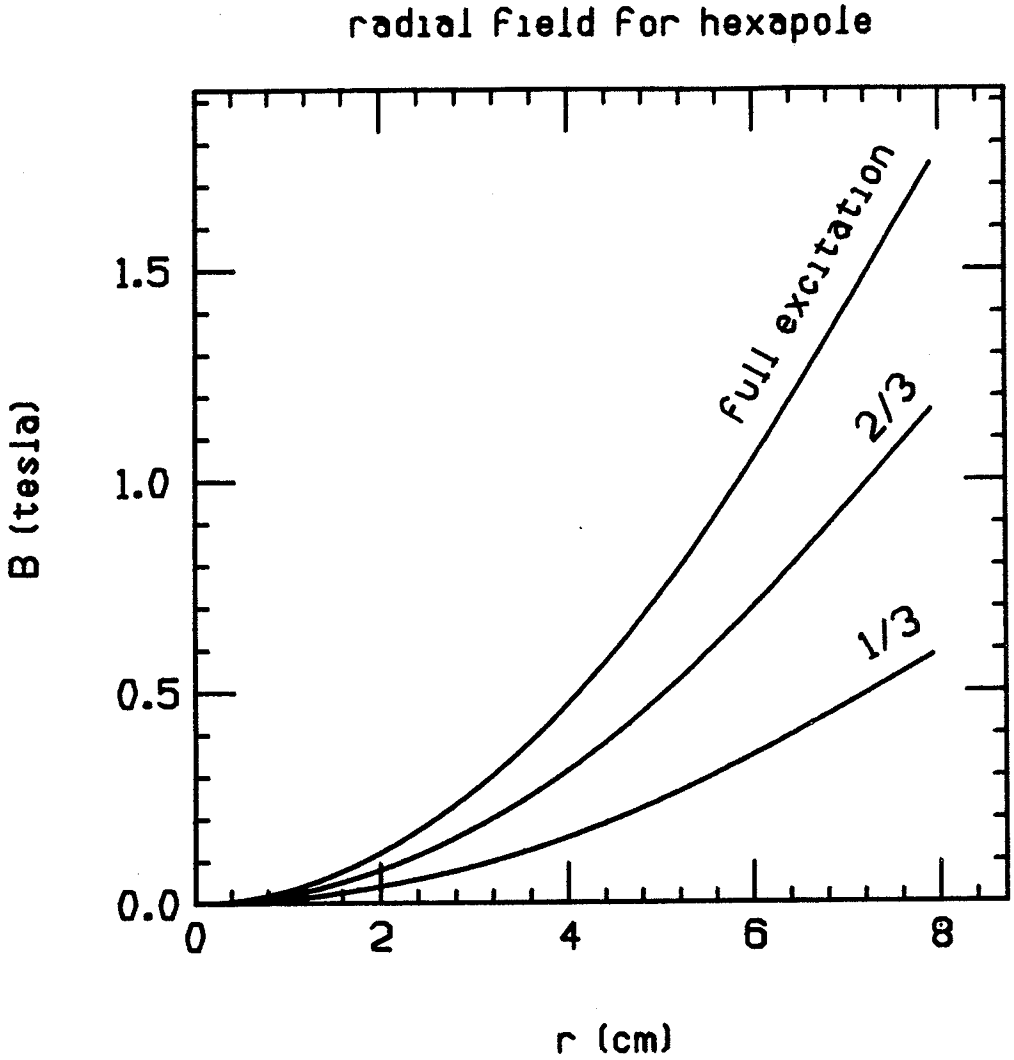

Figure 4. The required hexapole magnet radial field profile of the SC-ECR is shown, for 1/3, 2/3, and full excitation of the coils.